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Extending performance limits of turbine oils

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ABSTRACT

New turbine oils providing both extremely high viscosity index (VI) and improved boundary/mixed lubrication performance are investigated. Comparisons are made in both laboratory scale testing using typical journal bearing sliding surfaces (steel and white metal) and full scale testing using a hydrodynamic journal bearing test machine. The results from these studies demonstrate the effectiveness of new, high VI, turbine oils for reducing friction at machine startup and improving performance during full film operation.

1. Introduction

Increasing instability in the electrical power supply due to the rapid introduction of new energy sources such as wind and solar has led to an increase in the start and stop frequency of regulating power machines (commonly gas-fired turbines and hydro-electric power plants). These regulating machines are more often being forced to operate in non-optimal ranges. This can lead to higher bearing loads and increased oil temperature which can shorten the lifetime of the lubricant and can harm machinery. Further, due to the high startup friction provided by traditional oils and bearing materials, hydraulic jacking systems are often used to provide a lubricating film in thrust and radial bearings during start-up, however this extra system increases the complexity of the machine and the start-up procedure. Lubricants for these machines have traditionally been based on mineral oil and are generally considered hazardous to the environment which can be a significant drawback in renewable energy applications such as hydropower in which machines are placed in direct contact with sensitive ecosystems. However, developments in lubricant technology can potentially solve these issues and at the same time significantly improve machine performance.

Earlier work has investigated reduction of the start-up (breakaway) friction through the use of polymer materials [1] finding that significant reductions in the friction at startup could be realized with the use of polymer faced bearings. Texturing the bearing surface has been proposed to reduce sliding friction in the full film [2]. Texturing also helps to retain lubricant in the contact after shutdown and thus can reduce startup friction [3]. Reduction of this start-up friction through lubricant design presents a further method of improving startup characteristics. This could be especially useful for existing machines for which a lubricant change may be more realistic than replacement of the bearings.

While the viscosity index improving characteristics of polyalkylmethacrylates (PAMA and dPAMA) have long been known [4] a number of recent investigations have found improved lubrication properties using functionalized PAMA lubricant additives which attach to surfaces through polar bonds. Spikes [5] provides a discussion of the effect that various forms of boundary friction additives can have on both conformal and non-conformal contacts. Glovnea et al. [6] investigated the topic further to include surfaces with realistic roughness, finding that functionalized additives reduced the rolling-sliding friction in contacts with rougher surfaces. Further development of this topic by Müller et al. [7] led to a description of molecular characteristics to provide the thickest possible films, namely that the molecules should be large, have functional groups, and that the functional groups need to be concentrated in the molecule. Studies were continued with a full range of functionalized additives to further optimize the additives' molecular architecture by Fan et al. [8] finding that functionalized block co-polymers provided the thickest boundary films.

Muraki and Nakamura [9] investigated the effects of PAMA additives at the transition from thin film to sliding friction, observing thicker films at low speeds with significant shear thinning of the additives as speed increased.

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An investigation of the dynamic characteristics of the bonds between friction modifying additives and surfaces was conducted by Mazuyer et al. [10] finding that the boundary layer deformed elastically and that this deformation was reversible.

Polymer additives were used by Quinchia et al. [11] to successfully adjust the base viscosity of high-oleic sunflower oil. Viscosity at 40 °C and 100 °C were dramatically impacted. However it seems that the additives degraded the viscosity/temperature characteristics of the base oil as the viscosity index of the formulated lubricant decreased with increased additive concentrations. Similar investigations were made by Biresaw et al. [12] with biodegradable vegetable oils finding that while the oils had very high VI initially, their viscosity-temperature characteristics degraded with treatment for increased oxidation stability.

In laboratory tests, power loss reductions and equivalent film thickness were found to result from changing to a thinner synthetic lubricant in thrust bearings by New and Schmaus [13] and later by Glavatskih and Larsson [14]. Boehringer and Neff found significant improvements in machine performance upon changing to a di-ester based lubricant [15] in a full scale hydropower thrust bearing. Similar improvements in a full scale hydropower machine were found by Glavatskih [16] upon changing to an ester based lubricant in a combined thrust and journal bearing. Ferguson et al. [17] investigated ISO VG68, VG46 and VG32 in a large thrust bearing test rig and proposed using a numerical modeling software package to predict maximum bearing temperatures from oil bath temperatures and thereby predict bearing performance characteristics. Calculated results agreed well with experiments on a large thrust bearing. Lower power losses were found for lower viscosity grade (VG) and higher oil bath temperatures. Significant decreases in film thickness were also observed but it was argued that the lower film thickness was still adequate to maintain machine safety.

Investigations with journal bearings by Swanson et al. [18] in work with VI improvers found that the thermal performance of mineral-based oils could be improved to match that of synthetic lubricants. The effects of changing viscosity index was also investigated by Ma and Taylor [19] who found that increasing VI tended to decrease power losses, bearing temperature and film thickness. Separately, Dmochowski [20] and McCarthy et al. [21] found similar effects in their studies on the performance of journal bearings with high VI polyalphaolefin and ester based lubricants. However, power loss reductions in journal bearing studies have generally lower magnitude, percentage wise, than those found for thrust bearings and laboratory results have shown lower power savings than field experiences.

In the majority of earlier experimental work inlet or oil bath temperature has been kept constant in order to keep initial operating conditions equivalent for each of the lubricants. Power loss, film thickness and temperature were then found to compare performance of the varying lubricants. Temperatures throughout the bearing were used to calculate lubricant viscosity which was then compared, finding that in the case of the higher VI lubricants, viscosity was equivalent in the region of highest temperature (lowest viscosity) [20,21]. The findings from McCarthy et al. [21] showed that the film thickness was lower for the higher VI lubricants until the speed and load had increased to a point at which the minimum viscosities of the lubricants became equivalent. It was concluded that the reduced power losses provided by the higher VI lubricants were the result of lower bulk lubricant viscosity in the bearing.

High viscosity index lubricants were also investigated in a low speed journal bearing by Kasai et al. [22] finding that high VI lubricants led to reduced bearing friction in some cases and higher maximum oil film pressure when compared to a polyalphaolefin base oil. New forms of VI improvers such as comb polymers developed by Stohr et al. [23,24] have the potential to provide even greater performance improvements.

While the bearing performance of environmentally adapted lubricants with high concentrations of VI improvers was earlier documented [25], further improvements in additive technology have allowed for the formulation of lubricants with functionalized VI improvers. This allows for a lubricant with even higher VI and the benefits of functionalized PAMA in boundary lubrication. The current study begins by investigating the characteristics of a number of VI improvers for their potential to reduce friction at machine startup. Lubricants are also formulated using selected VI improvers and their performance is evaluated in a full scale journal bearing test rig. Testing in the full scale is accomplished to determine the operational limits of the new lubricants as compared to a standard ISO VG68 mineral oil.

2. Experimental study

Characterization of the startup characteristics of very high VI lubricants was conducted using two laboratory scale experimental setups. A reciprocating block on plate arrangement was used to examine the effects of a large number of starts and stops at low frequency. This reciprocating test rig was chosen for the extended portion of the study because of its highly stable and repeatable motion and results. Detailed studies on the stick slip effect at break-away were conducted using a block on disk arrangement to allow for more precise control of the acceleration and pre-loading of the contact. Testing of the lubricants' performance in full film hydrodynamic conditions was carried out using a full scale journal bearing test rig.

2.1. Lubricants

This study began by investigating a variety of lubricant additives for applicability both in the hydrodynamic lubrication regime and at break-away in the boundary regime. The characteristics of the optimum base oil/additive blends were then determined to develop a new generation of lubricants. The lubricants used throughout the study include white oil with high concentrations of VI improvers, mineral oil without VI additives, and synthetic ester with high concentrations of VI improvers.

Studies in break-away were begun with lubricants O, V, and G detailed in the upper portion of Table 1. From these initial studies,

Table 1
Characteristics of tested lubricants. MO = Mineral Oil, SE = Synthetic Ester, PA = 60% PAO and 25% Synthetic Ester blend, WO = White Oil, CP = Comb Polymer, HP = Hydraulic Package.

Lubricant	Base Oil	Viscosity (mm^2/s)		VI	Additive type	Concentration %
		40 °C	100 °C			
A	WO	14.9	3.86	163	dPAMA	15
B	WO	15.0	4.73	274	dPAMA	19
C	WO	14.7	5.35	364	dPAMA	9
D	WO	14.9	5.08	323	dPAMA	14
E	WO	14.9	5.67	394	PAMA	12
F	WO	14.9	6.47	475	CP	21
G	WO	15.3	7.87	581	HP	21
H	WO	14.9	4.11	195	dPAMA	15
O	SE	15.5	4.46	226	PAMA	4
V	MO	14.5	3.26	83	None	–
Z	WO	14.5	8.16	640	CP	20
VG68	MO	67.3	8.79	105	None	–
SV22	PA	20.4	6.81	340	PAMA	15
SE32	SE	32.1	8.46	259	PAMA	16
HV15	WO	14.8	8.29	637	CP	20
HV28	SE	26.8	13.5	519	CP	30